Available online at www.sciencedirect.com
ScienceDirect
Diamond & Related Materials 16 (2007) 1020–1024
DIAMOND AND RELATED MATERIALS
www.elsevier.com/locate/diamond

Ramp oxide termination structure using high-k dielectrics for high voltage diamond Schottky diodes

M. Brezeanu [a,*], T. Butler [a], N.L. Rupesinghe [a], G.A.J. Amaratunga [a], S.J. Rashid [a], F. Udrea [a], M. Avram [b], G. Brezeanu [c]

[a] Department of Engineering, University of Cambridge, Cambridge CB3 0FA, UK
[b] National Institute for R&D in Microtechnology (IMT), Bucharest 023573, Romania
[c] University Politehnica Bucharest, Bucharest 060032, Romania

Available online 27 January 2007

Abstract

The promising theoretical properties of diamond, together with the recent advances in producing high-quality single crystal diamond substrates, have increased the interest in using diamond in power electronic devices. This paper presents numerical and experimental off-state results for a diamond Schottky barrier diode (SBD), one of most studied unipolar devices in diamond. Finding a suitable termination structure is an essential step towards designing a high voltage diamond device. The ramp oxide structure shows very encouraging electronic performance when used to terminate diamond SBDs. High-k dielectrics are also considered in order to further improve the reliability and electrical performance of the structure.

Keywords: Electronic device structures; High power electronics; p-type doping; Schottky diodes

1. Introduction

The replacement of silicon with wide band gap semiconductors for fabricating power devices rated at more than 200 V has been extensively investigated in the last few years [1]. One of the applications in which wide band gap semiconductors devices would be preferred to silicon is as the freewheel diode in power electronic systems. The use of Si p–i–n diodes as freewheeling diodes in circuits working at high frequencies causes a significant disadvantage in power losses due to their bipolar turn-off. Superior performances are exhibited when unipolar silicon carbide Schottky barrier diodes are used in the same HV circuits. Due to their unipolar conduction, SiC SBDs have significantly lower turn-on and turn-off times compared to the p–i–n bipolar structure, and since they have a wide band gap they are capable of sustaining a breakdown field 10 times larger than that of silicon. With 300 V, 600 V and 1.2 kV structures already commercially available, SiC SBDs are now the leading candidate for replacing Si p–i–n diodes [2].

However, on a longer term, diamond Schottky structures might prove to be an even better solution than SiC SBDs [3]. Apart from having a larger critical field (10 MV/cm for diamond, 3 MV/cm for SiC), which would theoretically enable better off-state performance, measured carrier mobilities in diamond are nearly one order of magnitude higher than those in SiC (3800 cm^2/Vs for holes and 4500 cm^2/Vs for electrons in diamond, 120 cm^2/Vs for holes and 900 cm^2/Vs for electrons in 4H–SiC) [4]. Nevertheless, diamond has a major drawback: all known dopants have high activation energies [5], which lead to low concentrations of free carriers for conduction, and, consequently, to poor on-state performance. Boron (activation energy = 0.37 eV), which yields p-type characteristics, is, so far, one of the few dopants to allow some conduction at room temperature. In order to overcome the low activation rate problem and to fully exploit the excellent carrier mobilities values measured in intrinsic diamond, the diamond power Schottky diodes we have investigated (Fig. 1) have an undoped (intrinsic) drift layer, as opposed to the classical power SBD structures, where the drift layer is lightly doped. The high hole mobility in this metal–insulator–p+ (M–i–P) structure can compensate for the lack of carriers and yield an acceptable conductivity.

* Corresponding author. Tel.: +44 1223 748311; fax: +44 1223 748348.
E-mail address: mb470@cam.ac.uk (M. Brezeanu).

0925-9635/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.diamond.2007.01.016

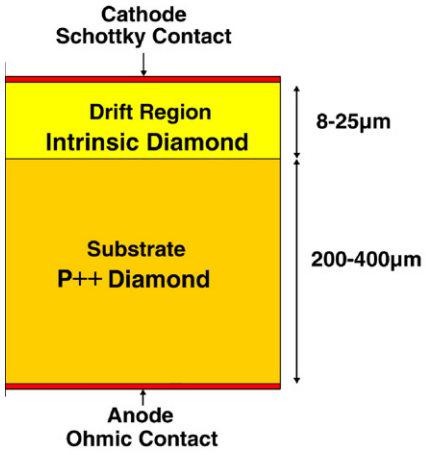

Fig. 1. Cross section of the diamond M–i–P structure.

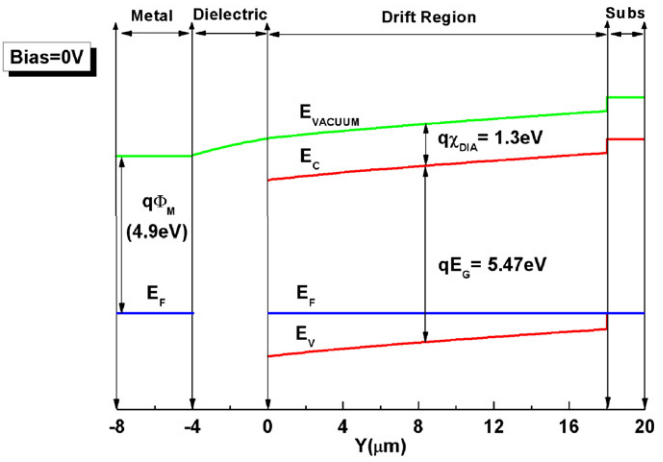

Fig. 3. Energy band diagram at $V=0$ V.

Due to diamond's high critical electric field, thin drift layers (typically between 8 and 25 μm) can withstand high off-state voltages (few kV). Diamond Schottky diodes with breakdown voltages up to 6.5 kV have already been demonstrated, thus proving its potential [6,7]. Finding a suitable termination is therefore the next step towards designing a competitive diamond unipolar device.

2. The ramp oxide termination

Due to the lack of shallow donor atoms, n-type regions are not available in diamond. Therefore, techniques commonly used for terminating Si or SiC devices, such as field rings or junction termination extensions, cannot be employed for diamond. This makes the field plate concept one of the few viable solutions. Various implementations of this concept have been investigated [8] and the best performance was obtained for the ramp oxide termination (Fig. 2). The structure has three key-parameters: the ramp angle (α), the dielectric thickness (T_{DIE}) and the field plate length (FP). In order to estimate the electrical performance of the termination, we have defined a virtual ("ideal") structure for which the cathode fully covers the intrinsic diamond layer, thus prohibiting the occurrence of any edge effects. If the termination efficiency (η) is defined as the ratio between the BV when using a particular termination and the BV of the ideal structure, then simulations predict that efficiencies up to 92% can be obtained with the ramp oxide structure [8]. In simulations, the drift boron doping was considered 10^{11} cm^{-3}, which was shown to be close to the 'quasi'-intrinsic condition [9,10].

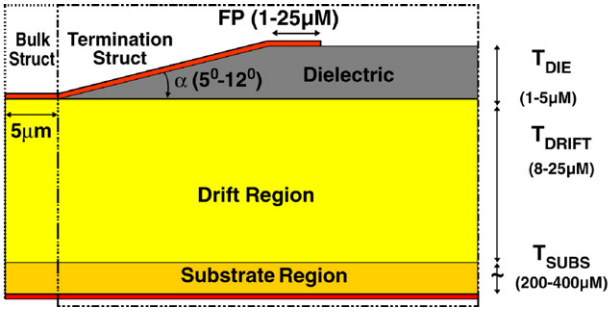

Fig. 2. Cross section of the diamond M–i–P structure with planar ramp oxide termination.

In Fig. 3, a schematic representation of the energy band diagram when no external voltage is applied to the device is included. SiO_2 was used as dielectric and the parameters chosen for the termination structure were $\alpha=5.7°$, $T_{DIE}=4$ μm and FP = 1 μm. The drift thickness was considered 18 μm, the substrate was 2 μm thick, the metal used for the cathode was gold (work function $=q\Phi_M=4.9$ eV), while the electron affinity of the oxygen-passivated diamond is 1.3 eV ($q\chi_{DIA}=1.3$ eV). The representation corresponds to a vertical cut through the device cross section (Fig. 2), from the cathode metal via the dielectric and the lowly doped diamond layer (the drift region), towards the highly doped diamond layer (the substrate). Due to its low doping, the drift layer is nearly completely depleted even at 0 V, therefore the conduction and valence energy levels are bent. At the edge between drift and substrate, due to the significant difference in doping, the energy levels also have a consistent variation.

Previously built on silicon and 6H–SiC [11], for the first time the ramp oxide was produced on diamond. In order to obtain a ramp angle lower than 12°, the range required for optimum electric behavior, three SiO_2 layers, with different thicknesses and impurities concentrations, were deposited on top of the intrinsic diamond region. Circular windows with 40 μm diameter were then defined in the oxide via photolithography. Provided that the etching rate of an oxide layer increases with the concentration of impurities, the three layers etch with different speeds when immersed in a P-etch solution, thus creating the ramp. After the evaporation of gold for the Schottky contacts, an M–i–P structure with $\alpha=11°$, $T_{OX}=2.2$ μm and FP = 1 μm was obtained. The measured off-state characteristic (Fig. 4) exhibited a breakdown voltage of 1.1 kV for a nominal drift thickness of 13 μm. This value of 1.1 kV is below the theoretical predictions. Good simulation–experiment matching was obtained for a drift thickness of approximately 8.5 μm (Fig. 5). The discrepancy is mainly due to the fact that research in using diamond as a semiconductor is at an early stage and many issues still need to be addressed. To